Challenges Facing Successful Development of Long Life, High Temperature, High Efficiency/Power AMTECs for Space Applications

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Abstract. The technical challenges confronting development of Alkali Metal Thermal-to Electric Converters (AMTEC) for up to 15 year life on NASA Mars and outer planetary missions are significant, although approaches to solutions are understood by many investigators. The technical challenges include material issues, specifically involving decomposition of materials or chemical reaction between materials in contact; electrical issues, including electrical shunts that reduce output power and possibly plasma discharges within AMTEC converter units in which potentials in excess of 5.25 Volts exist; and heat and mass transport issues which can have major effects on the converter unit's power and efficiency.

INTRODUCTION

The critical problems facing development of AMTECs capable of long term, high performance in space missions are generally somewhat misunderstood by many of those interested in achieving successful application of AMTEC technology. While it is generally perceived that there are well defined technological hurdles to overcome, such as fabrication of high performance, highly reliable braze seals between sodium beta" alumina and structural components of AMTEC devices, the appropriate route to such accomplishments is not a matter of consensus. [Williams, et al, 2000] In general, the solutions to such problems have been scheduled according to rigid timetables that are quite demanding, apparently under the belief that these solutions are, "just engineering" and are programmable in advance.

Technological problems which confronted the AMTEC development efforts over the past few years (for space applications) included the long term stability and reliability of critical components including structural components (Kupperman, et al, 1991, Kramer, et al, 1998, Svedberg and Sievers, 1998, Williams, et al, 1993), electrodes, (Ryan, et al, 1991, 1993, 1994a, 1994b, 1998a, 1998b, 1999a , 2000, Shields, et al, 1999, Williams, et al, 1990c) and the solid electrolyte. (Cole, et al 1979, Hunt,. et al 1979, Ryan, et al, 1994c, Steinbrück, et al, 1993, Williams, et al, 1995, 1997b, 1998b, 1999a, 1999b, 2000) There were significantly different approaches to these problems, which on the one hand could be expressed as a view that the current components would work, if fabrication and tests were successful; and on the other hand, that changes in materials were required in order to achieve required stability and reliability. The merits of testing components vs. testing complete devices were extensively discussed, often from opposite advocacy positions, although it eventually became clear that both approaches were necessary. The development of understanding of the causes of limited performance and reliability was only a subtext to this discussion, with emphasis entirely on achieving stated goals. Unfortunately, regardless of the technological arguments, the programmatic plan called for expenditures and achievements that required that accomplishments be achieved according to a generally inflexible funding timetable. Under such a constraint, obvious and well demonstrated improvements might be shunted aside by the ongoing programmatic juggernaut because schedule and cost do not permit modification of the plan and creative technological solutions which require detours to develop technical understanding are opposed whenever suggested and could be introduced into the project only with extreme difficulty.

This paper will discuss the current state, and recent history, of the resolution of technical issues in AMTEC work through the last 3 years, and the remaining technological problems and approaches to resolving them. It will forego a general description of the AMTEC device as this may be found in many of the referenced papers, in greater detail than would be possible here. The paper will only discuss technical issues specific to AMTEC and not address certain other important requirements which any power system for space applications must also meet. The paper will not address mechanical stability, except where it is impacted by degradation processes; nor will it address corrosion issues which might result from introduction of contaminants into the AMTEC device. This paper will also address the equally serious problem of achieving these ends in a community in which the extreme approaches are "use only risk-free technology" and "everything must be newly developed." A more productive approach would be one that emphasizes development of understanding of mechanisms and processes in order to solve technical problems or to clear technical hurdles. Micro-scheduling assures that "faster" and "cheaper" always dominate "better" throughout the development process; and there is seldom sufficient flexibility to incorporate technical advances in the "official" design. Micro-scheduling not only constrains the overall time or budget for the project, but also constrains schedule and budget at all times during the project's existence.

RESULTS AND DISCUSSION

Materials Stability Issues

Unstable Materials
For a device such as AMTEC to perform adequately at high temperature, for several years, materials stability is a critical issue. Materials that are convenient to work with, or are readily available must be checked in the literature before using them to be sure they are stable in the AMTEC environment.

Even before 1990, JPL suggested that known volatile and reactive elements be removed from hot regions of the AMTEC cell where their volatility would be non-negligible over the lifetime of the proposed device. One of the first examples was the copper current collection system, which extended to the cathode and its wire wrapping. Molybdenum was substituted in an early phase of the ARPS program. Later, several laboratories within the ARPS program attempted a switch to refractory metal construction, based on the well-known volatilities of ferrous and refractory metals. Several months were devoted to building and testing AMTECs constructed from Haynes 25 alloy as a replacement for stainless steel, despite the fact that there were sufficient data in the open literature detailing its long-term instability at temperatures on the order 1150K. In spite of both physical evidence that rhodium reacted with manganese and ferrous metals, as well as phase-diagram information indicating the same thing, effort was spent testing rhodium high reflectivity coatings on ferrous alloys and finding them to be unsuitable because of Rh-alloy inter-diffusion.

Fused silica or fused silica containing insulation was used in AMTEC converters external to the power conversion unit, where it was exposed to high temperature and nominal vacuum. Temperatures of the insulation could reach 1073K. SiO_2 is known to lose oxygen at T< 1273 K, with the resultant SiO also being volatile. In addition, evolved oxygen would certainly react with the power conversion unit construction material, whether ferrous or refractory, at these temperatures. For example, oxygen from SiO_2 can destroy Nb1%Zr from the outside, if all the Zr is oxidized. Slight degradation due to this problem was observed on short term tests, but resulted in no decision relative to long-term tests.

Construction Material
There already existed substantial information about the properties of alloys at AMTEC operating temperatures from work before 1990, which was useful in evaluation of these materials for application in AMTEC cells. (El-Genk, et al1999, Mital, et al 1999, King and El-Genk, 2000a. 2000b, Kramer, et al 1998, 1999a, 1999b, 2000, . Kupperman, et al 1991, Svedberg, and. Sievers, 1998, Williams, et al 1993) Almost as soon as the decision was made to go to construct AMTECs from refractory metals, a decision which took approximately two years,, the decision to use Nb1%Zr was also made. Technologists suggested that molybdenum/rhenium alloys or another commercially available niobium alloy, C-103 (Nb with several percent W and Hf, an alloy equally available, stronger at high temperature, and with lower thermal conductivity than Nb1%Zr), might be superior alloy choices, but Nb1%Zr was chosen instead. More recently, molybdenum/rhenium has been selected and this is a more appropriate choice

because it meets some requirements of AMTEC and its properties have been thoroughly documented. However it probably has too low a thermal expansion coefficient to match sodium beta alumina solid electrolyte (BASE); it probably is a less-than-ideal wall material because of relatively high thermal conductivity from the hot to the cold side; and it certainly cannot be allowed to get very hot for very long in an oxygen-containing atmosphere, although its characteristics in this regard are superior to Nb1%Zr.

High Temperature Seal and Sodium Wick
The high temperature seal between BASE and either metal or insulating ceramic structural components is a ~~very~~ critical component of the AMTEC cell. The wick which transports liquid sodium from the low temperature end of the AMTEC cell to the high temperature plenum and BASE tubes is also a critical component. Both of these components have similar constraints with respect to structural and functional stability and reactivity toward other AMTEC components. However, there are perhaps fewer constraints than on the most critical AMTEC components, the solid electrolyte and the cathodic electrode.

Earlier work on AMTEC devices with high temperature seals utilized commercially available Ti-Ni and Ti-Ni-Cu alloys with solidus around 1233K. Many of the seals performed satisfactorily for up to several thousand hours, but the yield of successful brazes on fabrication was never close to 100%. Some of these seals also failed during operation, after appearing to have good properties at room temperature. So far Ti-Ni still has the best track record of any braze. It cannot be used at the highest AMTEC temperatures but may be useable to 1100K if warm-up from about 1050K is fairly slow. Ti-Ni, or possibly Ti-Fe with a higher solidus, may be useful in some near term tests of AMTEC devices, but it should not be considered for the final application and parallel seal development must proceed. Subsequent work on Ti-Zr-V brazes was somewhat less successful, due to greater extent of reaction of the active metals with BASE. Some work with compression seals using tantalum has also been successful, but compression bonds are a likely source of sodium leaks and lowered cell voltages. Systematic approaches to selection of seal materials have been cursory to this point. It is fairly obvious that tantalum is the best single element refractory metal candidate for a compression seal because of its thermal expansion coefficient match to BASE and its generally good mechanical properties. JPL has just begun a systematic study of the reactivities of potential braze constituents toward BASE, with indications unfavorable for titanium and promising for vanadium. This is only the beginning of the first step in building a stable seal for refractory metal to BASE. If a seal to another ceramic is required, equivalent investigations must be made to verify its stability to the braze. It is very likely that unless the compression seal works adequately, it will be necessary to utilize a braze which contains at least a minor percentage of a brittle intermetallic compound. If the braze matrix is ductile, the presence of some intermetallic should be acceptable.

One of the most timely changes in AMTEC design was the switch from stainless steel to refractory metal based wicks and high temperature evaporators,(Anderson, 1992, Anderson et al 1993, Crowley and Izenson, , 1993, El-Genk, and Tournier, 1998, .Izenson and Crowley, 1993, 1996, Sievers, et al, 1999, K. Tanaka, et al, 1993), .Tournier and El-Genk, 1999, 2000) which occurred with a consensus of AMTEC workers. The refractory metal wick is not without problems; occasionally these wicks leak or dry out below the hot end, but in general they have been successful in recycling liquid sodium. On the other hand, details of their performance with liquid sodium are not well understood. Tests employing alcohol have been used to verify wicking at room temperature. Tests with liquid sodium are only carried out after the wick is incorporated into and AMTEC device. While the refractory wicks should be considered a successful development, greater characterization of their behavior in contact with liquid sodium at AMTEC operational temperatures could be extremely helpful in designing them for optimum performance and long term stability.

Work on the metal to BASE seal and the liquid sodium wick has provided functional components which may be performing at well below optimum levels. There has been only some effort expended in developing understanding of the processes which may limit performance in both of these cases. Several propositions which might explain seal failure have been presented, but the issue is not resolved because the data is insufficient and the analysis does not strongly support one explanation. (Williams, et al 1998b, 1999a, 1999b, 2000). The situation with the wick is different: it is clear that the wick transports sodium but it is not clear if the wick performance is acceptable, and no hypotheses related to wick performance below optimum have been seriously considered.

Electrodes

Several well behaved AMTEC electrodes have been known and extensively studied for about 15 years. (Asakami, et al, 1989, 1990, 1991, McBride, et al, 1987, Schuller, et al, 2000,Weber, 1974, Wheeler, et al, 1988, Williams, et al 1986, 1988, 1989, 1990a, 1990b, 1992) Direct comparison of electrodes has been difficult, however, due to the small number of labs preparing AMTEC electrodes and the variability of electrode performance with parameters relating to their operation at typical AMTEC cell conditions. Two electrodes with good performance were titanium nitride, developed at Ford and AMPS and studied at several other laboratories including JPL, and rhodium/tungsten until very recently investigated only at JPL. Both electrodes should have received careful study and lifetime comparison at several laboratories, and eventually this need was filled. (Ryan, et al 1999a, 2000, Shields, et al, 1999) However, on the non-technical side, the expense and scheduling delay in investigating rhodium tungsten electrodes slowed this technically obvious comparison for over a year. The specious issue of the reproducibility of rhodium tungsten alloys was introduced, despite the fact that JPL had reproduced high performance electrodes of this composition many times. Eventually, studies at Oak Ridge and Texas A&M demonstrated both the facile production and high performance of rhodium/tungsten electrodes. TiN electrodes are still worthy of further consideration, especially for lower temperature applications, but the emphasis on TiN work was shifted from optimization to quality control and reproducibility. It is still unclear if anyone has demonstrated a nearly optimized titanium nitride electrode. Moreover, reproducibility of an unoptimized electrode is of questionable value. There is a possibility that other new electrodes can be made with still superior performance and lifetime compared with rhodium tungsten can be made. (Ryan, et al , 1999b) Nevertheless the performance and life characteristics of the rhodium/tungsten electrode are such that the electrode issue can be considered solved. The very substantial success of the AMTEC electrode development effort, over about 15 years, can be traced entirely to the firm emphasis placed on the development of fundamental understanding of electrode processes, emphasized by the first experimentalists at Ford and later by experimentalists at JPL and other laboratories. (Hunt, et al 1975, 1978, 1981, Hunt and Weber, 1982, Weber, 1974, Wheeler, et al 1988, Williams, 1986, 1988, 1989, 1990a, 1990b, 1992b 1997a, 1998a) This occurred in parallel with the publication of large numbers of systems studies, which generally predicted AMTEC performance optimistically, but did not even recognize many of the internal loss mechanisms which were being identified and solved in the laboratory.

Solid Electrolyte

Studies at JPL and other laboratories indicate the kinetic stability of sodium beta" alumina to 1273K in vacuum or sodium vapor, and to 1173K in liquid sodium for hundreds to thousands of hours, with no decomposition -of the sodium beta" alumina phase observed during or after these accelerated tests if elements known to react with BASE are excluded. (Cole, et al 1979, Hunt,. et al 1979, Ryan, et al, 1994c, Steinbrück, et al, 1993, Williams, et al, 1995, 1997b, 1998b, 1999a, 1999b, 2000) The lifetime of pure BASE in an AMTEC cell at 1123K is estimated to be sufficient for spacecraft applications. There is evidence from SETC electrical tests, mass loss studies at 1273K and above, and XRD studies of annealed BASE that a minor constituent of BASE, either sodium carbonate, Na2CO3, or sodium meta aluminate, Na_2AlO_2, is slowly lost from BASE at temperatures near 1273 and somewhat lower. Both of these phases are also known to decompose with significant rates in vacuum at temperatures below 1273K. Both phases can be eliminated from BASE ceramic by annealing it in an air atmosphere under a gently packed mixture of powdered sodium beta" (80%) and beta (20%) alumina, for 100 hours at 1673K. The resultant ceramic shows greater phase purity of the beta" phase than before treatment by XRD, appears qualitatively to be stronger, and has a somewhat increased ionic conductivity at 1123K compared with untreated standard Ionotec BASE. This procedure was successfully carried out with both Ionotec and Cerametec (Williams, et al, 2000) The surface morphology is not radically changed and several AMTEC electrode materials have been sputtered onto these treated tubes with good adherence. Treated tubes can be handled briefly in air, but should not be stored for long times in an ambient air atmosphere containing water vapor or carbon dioxide, or reformation of sodium carbonate may be possible.

Sodium beta"-alumina is unstable with respect to reaction with metals such as chromium and manganese, probably zirconium, and to a lesser extent titanium, at temperatures of 1173K and perhaps somewhat lower (Williams, et al, 1998b, 1999a, 1999b). There is relatively little reaction with manganese at temperatures as low as 1023K; however, very long periods of exposure may result in reaction with these reactive metals at lower temperatures, if the reactive metals directly contact the BASE or can reach it via evaporation, as in Mn and Cr from stainless steel.

The success of the evaluation of BASE ceramic can once again be ascribed to the rigorous adherence to an experimental approach designed to provide detailed understanding of degradation mechanisms, both within and

outside of the normal AMTEC operating regime. Little could have been accomplished with testing limited to the proposed AMTEC operating regime, in spite of the wild fluctuations of those suggested parameters in various studies. The performance and life characteristics of the sodium beta" alumina solid electrolyte electrode are such that the electrolyte issue can be considered to be solved in principle. In practice, AMTEC devices are still being fabricated with the undesirable minor constituents present.

Electrical Issues

Insulator Shorting
The design of AMPS series connected power units places up to eight BASE tubes in a common low pressure chamber and connected to a common high pressure sodium vapor plenum. All but one of these BASE tubes must be mounted on insulating stand-offs composed of alpha-alumina or sapphire. These stand-offs serve to isolate the individual cells , and will perform as long as their resistance to either electronic or ionic current is greater than 5-10 ohms. However, a great deal of research carried out for application to sodium lamps on the compatibility of sodium gas with alpha alumina, sapphire and other ceramics, as well as experiments at JPL testing compatibility of oxygen free sodium with alpha alumina at 1173K for 500 hours, have shown that sodium reactions with alpha alumina or sapphire are possible but slow.(Williams, et al, 1998a, 1998b, 1999a) Additional insulating materials are being investigated at AMPS, but accelerated testing should also be performed on these components since the requirements for space applications can be as long as 15 years.

Plasma Discharge
JPL has demonstrated a phenomenon that, so far, can only be explained by a plasma-short through the alkali metal vapor between electrodes, which may be on a single section of BASE, or on two separate pieces of BASE. (Williams, et al 1992a, 1992b, 1994) With sodium vapor, this phenomenon occurs at potential differences of greater than 5.5 volts, but typically between 6 and 10 volts, and is typically very noisy, turning on and off frequently. Identification of the mechanism was made possible by observation of the similar but less noisy behavior in potassium vapor with electrodes on potassium beta" alumina, K-BASE, where the phenomenon started at about 4.3 volts and increased linearly in current as the voltage was raised, with the potential applied between two non-contacting electrodes on different pieces of K-BASE. (Williams, et al 1994) The only other study on plasma discharge has been performed by AMPS, under a different experimental procedure. (Barkan and Hunt, 1998) In that test they failed to find plasma discharge, at voltages <100 volts. The test used pointed wires in low pressure sodium vapor as the samples, instead of AMTEC electrodes as described in the JPL paper which reported these discharges. The differences in the test procedures account for the differences in results, and sets of experimental data from both studies are probably correct . Both thermodynamics and the phenomenology of electron emission from hot surfaces support the JPL conclusion. In addition, multi-BASE-tube series connected AMTEC devices at AMPS are reported to have maximum voltages of 5-6 volts, although generally there is no attempt to run these devices at higher voltages. Plasma shorting may be leading to loss in some of AMPS's series connected cells and should be investigated in more detail. Correction of this problem would require redesign of AMPS multi-tube cells to avoid plasma discharge problems or operating conditions that prevent the AMTEC converter from going to open circuit or above 5 V

Electronic Conductivity of BASE
Limited voltage produced by multi-tube AMTECs has been occasionally ascribed to the electronic conductivity of the BASE. This problem, were if it were true, would potentially be very limiting to AMTEC applications, and probably not subject to improvement. In fact, high electronic conductivity of BASE is inconsistent with a large number and variety of measurements, most specifically early AMTEC tests with cold hermetic seals, an overpressure of argon, and hot sodium in the bottom 10-15 cm of a closed end Cerametec BASE tube.(Hunt, et al 1975, 1978, 1981, Hunt and Weber, 1982, , Wheeler, et al, 1988, Williams, et al 1986, 1988, 1989, 1990a, 1990b, 1992). Those cells were run with a large cool cylindrical condenser surrounding them, except for a smaller cylindrical heat shield about 3.5 cm in diameter around the hot zone at one end of the BASE tube. BASE temperatures in the hot zone routinely exceeded 1200K, sometimes reaching 1240K for several hours. These cells routinely provided open circuit voltages above 1.4 to 1.5 volts and, occasionally, above 1.6 volts at the highest temperatures achieved. Cell voltage dropped precipitously with very small cell currents, as expected from the Nernstian behavior of the cells in this temperature/pressure regime. The electronic conductivity of BASE may categorically be stated to be a non-

existent problem in further AMTEC development. . However, the problem of limited voltage remains, as discussed below, but should not be ascribed to electronic conductivity.

Heat and Fluid Transfer Issues; The Open Circuit Voltage

Sodium Vapor Transport in the Low Pressure Containment; Heat Transport from the AMTEC Cell Hot End to the Cold End

Efficient sodium vapor transport from the AMTEC cathode to the condenser is critical to achieve high cell voltage, power, and hence efficiency.(Crowley, 1991, Johnson, et al 1994, Sievers et al 1993, Tanaka, et al 1992, Tournier, et al, 1998,. Weber, et al 1992) On the other hand heat transport from the hot end of the AMTEC cell to the cold end results in a significant waste of useable heat and a reduction in cell efficiency. (Ivanenok, et al, 1995, Ryan, et al 1993, Suitor, et al 1992a, 1992b, Underwood, et al, 1990) Thus the requirements for efficient sodium transport and limiting waste heat transport are directly contradictory, as has been recognized for some time. Additionally, it appears that most model calculations of AMTEC performance impose a condition that sodium condense only at the coldest point in the AMTEC cell, and that furthermore, the temperature gradient can be specified without empirical data derived from tests on actual or dummy cells.

It may be that adequate heat loss from the cold end is an appropriate assumption in laboratory tests where active cooling of the cold end is employed. Such a level of heat loss cannot be assumed in a performance study which takes no account of how adequate heat rejection is to be achieved. Nor can it be assumed for tests run under realistic conditions, where the condenser is cooled passively. If current passive cooling designs are inadequate to maintain a sufficiently cool condenser, more effective passive cooling designs consistent with space applications must be applied.

Liquid sodium transport in wicks

Although the refractory wicks introduced into AMTEC cells appear to pose no problems with respect to reactivity with other AMTEC components, details of their performance with respect to liquid sodium are difficult to extract from test results. (Anderson, e al 1992, 1993, Crowley and Izenson, , 1993, El-Genk, and Tournier, 1998, .Izenson and Crowley, 1993, 1996, Sievers, et al, 1999, K. Tanaka, 1993,.Tournier and El-Genk, 1999, 2000) Tests employing alcohol have been used to verify wicking at room temperature. Tests with liquid sodium are carried out only after the wick is incorporated into and AMTEC device. While the refractory wicks are a successful development, greater characterization of their behavior outside of an AMTEC cell but with liquid sodium at AMTEC operation temperatures could be extremely helpful. We have no measurements of actual liquid sodium flow rates vs. pressure gradient in these wicks, nor do we know if liquid sodium reaches the extreme hot end of the wick. If the liquid sodium evaporates at a surface below the hot end of the wick and at a cooler temperature, substantial losses in cell open circuit voltage and power density while drawing current may occur. We also especially do not have detailed understanding of liquid sodium flow in a non ideal wick where the porosity is a distributed function from place to place in the wick. Finally, detailed evaluation of liquid sodium flow in refractory wicks may provide unexpected fundamental information relating to fluid transfer, corrosion processes, and grain growth which cannot be precisely defined prior to investigation.

Sodium Transport via Leaks, Electrolytic Shorts, Electronic Shorts; The Current /Voltage response

A large amount of power generated by the AMTEC is lost due to the low open circuit voltage, typically about 0.5 V. in current multi-tube conversion units In AMTEC experiments done some time ago, maximum efficiency was obtained near 0.5 volts, and maximum power at about 0.4 volts, with discharge current densities on the order of 1-2 amps/cm^2. Open circuit voltages were measured as high as 1.6 volts, and were typically 1.4 - 1.5 V. Single cells with hot braze seals have attained open circuit voltages as high as 1.2-1.4 volts, due to a small unavoidable electric shunt at the seal/BASE interface. (Williams et al 1998c) Placing six cells in a common container, so that the sodium flux from each affects all of them, should only result in an additional loss of about 0.1 volts per cell. (Williams et al, 1990a) Hence, in multi-tube series connected arrays of typical size, each cell should be producing an open circuit voltage of 1.1 volts. In fact, in such arrays, the maximum voltage is typically 0.5 to 0.6 volts per cell. (Tournier, et al, 1997, 1998 Underwood, et al, 1992b, et al, Williams, et al, 1998) Clearly other loss mechanisms are in effect. Specifically, this suggests that the AMPS multi-tube series connected cells are leaking at a rate corresponding to operation at about 0.4-0.5 volts below open circuit; or that the sodium pressure on the hot side is only about one

thousandth what it ought to be for the stated hot side temperature (this explanation is of low probability because these cells can generate quite substantial output currents); or that electronic shorts exist. More than one of these problems may exist, and there are other less likely candidate mechanisms that would reduce performance. Any of these phenomena cause a performance deficiency too large to be accepted. They can also impact life because cells with better performance provide more latitude in designing operating characteristics, hence allowing longer life. The first step toward solving this problem is to develop an understanding of the importance of the performance degradation issues including but not limited to those listed above. The next steps include many potential paths, depending on the outcome of the performance degradation study. This issue is tractable, but it is not possible to reasonably state the route or full set of alternative routes to a successful solution ahead of time. In developing understanding of the causes of performance degradation, it is significantly likely that we will discover effects which can not be reasonably anticipated at this time.

CONCLUSIONS

This paper has discussed the major challenges confronting successful development of long-lived, high-performance AMTEC devices for space applications. The discussion is limited to AMTEC-specific issues, and generic issues appropriate for any power conversion system have been largely ignored. An example of such an issue is the electrical feed-through from the inside of the AMTEC device housing to the outside. This feed-through has very critical requirements, but similar requirements pertain to other elevated temperature power devices. This paper has also not discussed many performance enhancement routes that are not critical or sufficient to produce a viable high performance long life device, and not of such promise that they would allow a major reduction in operating temperature, for example. Routes to moderate improvement in cell output power, such as optimization of current collecting networks, have also not been discussed as the current technology works adequately, and does not limit AMTEC device lifetime. (Ryan, et al, 1991, 1992, 1995, Tanaka, et al, 1992)

The paper describes problems that are already solved, for example the AMTEC cathode, as well as potential routes to solutions in cases where the nature of the problem is fairly well understood, such as the BASE-to-metal seal. It has also described aspects of AMTEC technology and performance where improvement should be expected, but where such improvement is dependent on a significant effort in developing understanding of which of numerous possible and some unforeseeable mechanisms result in loss of performance. In some cases, most notably the low open circuit voltages obtained in series connected cells sharing a common housing, the nature of the problem allows one or more of many explanations, which are not yet verified, nor are they entirely explicable. The overall cell performance, stated as efficiency, power density, or specific power, is also less than it should be , and is influenced by even more aspects of cell fabrication and operating parameters. Determining the nature of the problem will in this case logically lead directly to solution, as none of the potential contributing problems appears to be intractable, and high levels of performance of all requisite components have been observed. Systems studies can account for the performance of AMTEC devices, but in using a relatively large number of adjustable parameters to fit a relatively simple mathematical function, their results are ambiguous with separate, definitive measurements of the parameters.

The appropriate route to attack these sorts of problems is to examine in detail, experimentally, all reasonable loss mechanisms using techniques which are much more sensitive than device performance. Experiment exploration of this nature quite generally leads to understanding including the role of loss mechanisms and failure modes not initially predicted. Specific cases of the discovery of unanticipated phenomena in the history of AMTEC include the beneficial effect of enhanced activated transport modes on rhodium tungsten electrode, and the deleterious effect of manganese and chromium vapor of some electrodes and the BASE ceramic. (Williams, et al, 1989, 1998b, 1999a, 1999b) However, to reach such a solution, a program is needed that is flexible enough to adapt to new knowledge as it is forthcoming without rigid milestones. The most successful and productive work carried out on AMTEC programs since the invention of the device by Weber and Kummer in the 1960's has been work oriented toward understanding of problems, which in turn leads to understanding of the range of potential solutions.

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